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by

W.P.Rodden

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(6) # STATE-OF-THE-ART IN UNSTEADY AERODYNAMICS,

by

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PREFACE

The accurate prediction of unsteady air loads is essential to avoiding problems and assuring safety in the many interdisciplinary regions involving aeroelasticity and the dynamics of active controls. However, the methods to predict such airloads are complex and intricate. It was considered essential to specify standard configurations and parameters, and to encourage pioneering NATO scientists to report their results early. This would provide bases for evaluation and improvement of later and following developments by other countries. The first cooperative effort involved isolated surfaces in subsonic and supersonic flow, and is reported by D.L.Woodcock in AGARD Report No.583 ("A Comparison of Methods Used in Lifting Surface Theory", 1971). The noticeable success led to another effort on interfering lifting surfaces and is reported by W.P.Rodden in AGARD Report No.643 ("A Comparison of Methods Used in Interfering Lifting Surface Theory", 1976). Both are supplements to the AGARD Manual on Aeroelasticity, Vol.VI. The latter effort and report has also proved to be highly successful.

New developments are rapidly emerging in unsteady aerodynamics. The aeroelastician will continue heavy reliance on prediction of airloads from theoretical methods. A terse description of the new state of the art was required and has been very competently provided by Dr Rodden in this report. The Sub-Committee on Aeroelasticity and Unsteady Aerodyanmics will use this framework to establish high priority, cooperative, comparative computational AGARD programs. Transonic and control surface unsteady aerodynamics are likely selection candidates.

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STATE-OF-THE-ART IN UNSTEADY AERODYNAMICS

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SUMMARY

A brief survey of new developments in unsteady aerodynamics is made as a proposal for establishing another comparative computational AGARD program. Candidate topics include supersonic interference, transonic flow, wing-body interference, control surfaces, rotary loads on T-tails, interference effects of vortex shedding, and rotating blades. A selected bibliography is presented for each topic to illustrate the present state-of-the-art and its near-term future potential.

INTRODUCTION

This paper is a survey of the state-of-the art of unsteady aerodynamics only in a limited sense. The survey is not intended to be a critical evaluation of the references that constitute the current status, but rather to outline areas which may be of general interest to the Structures and Materials Panel so that another comparative computational study might be made similar to those of Woodcock[1] and Rodden[2] on comparisons of unsteady aerodynamic calculations for isolated and interfering lifting surfaces, respectively.

Recent surveys of research problem areas have been presented by Laschka[3] and McCroskey[4]. These discuss more advanced topics than those mentioned here.

Seven problem areas are proposed here and related recent papers are cited. The first six areas concern fixed wing aircraft and the seventh considers the effects of rotation in rotorcraft and turbomachines. The areas suggested for fixed wing aircraft include further supersonic studies, renewed transonic studies, wing-body interference, control surfaces, rotary loads on T-tails, and interference effects of leading- or side-edge vortex shedding.

SUPERSONIC INTERFERENCE

This subject was one of the comparisons in Ref. 2 but only limited calculations by two methods were compared. A large number of new approaches have appeared recently and it would seem reasonable to invite applications of these new methods to some of the standard AGARD configurations. The new methods with which the author is familiar include: the integrated potential formulation of Appa and Jones[5], the kernel function method of Cunningham[6], the finite element doublet method of Giesing and Kálmán[7], the finite element method of Morino, et al.[8,9], the doublet-lattice method of Brock and Griffin[10], the constant pressure panel method of Roger[11], the modified Mach Box method of Chipman[12], and the characteristic box method of Schmid[13]. There are significant differences among these new approaches and the extent to which computed results by each agreed would add considerably to an improved understanding of supersonic interference.

TRANSONIC FLOW

Sonic calculations by a collocation method were presented in Ref. 1 for isolated wings. Much progress in unsteady transonic flow theory has occured since the calculations in Ref. 1 were collected. A recent survey by Tijdeman[14] has summarized the significant developments of the past three years. Table 1 of Ref. 14 is reproduced here as Table 1 and the 20 references are also cited here[15-34]. Most of these works concern two-dimensional airfoils but a few treat the three-dimensional case.

In his concluding remarks, Tijdeman notes "that inserting the effects of thickness, incidence of the airfoil and of shock waves in inviscid theory is an important step forward. However, as shown..., the effect of the boundary layer is of the same order of magnitude and thus of the same importance. Therefore, realistic improvements from the aeroelastician point of view may be expected only if also the second step is made, namely the inclusion of the boundary layer. In this respect the study of the behavior of boundary layers under unsteady flow conditions will become important." The importance of viscous effects has also been observed in hinge moment predictions for control surfaces by Gray and Davies[35], and will be discussed below, but it is interesting to note here that thickness, incidence (which may have larger effects than thickness), and viscous effects should be treated together (or all three effects neglected) in achieving experimental correlations.

The variety of new transonic techniques can also be evaluated by establishing new standardized configurations. Two- and three-dimensional configurations might be based on the NACA 64A410 airfoil analyzed so thoroughly by Magnus and Yoshihara[25,26], or the NLR 7301 airfoil, which is representative of the new generation of supercritical airfoils, and is currently undergoing extensive testing and analysis. Reynolds numbers as well as Mach numbers should also be selected among the governing parameters.

WING-BODY INTERFERENCE

A survey of wing-body aerodynamic interaction was presented by Ashley and Rodden[36] in 1972. A number of advances at subsonic speeds have been made since then. An interference theory has been developed by Giesing et al.[37] in which the lifting surfaces are treated by a combination of the Doublet-Lattice Method, Slender Body Theory, and the Method of Images. A panel method for steady flow for general configurations has been developed by Labrujere and Sytsma[38]. Bennekers, Roos, and Zwaan[39] have combined the Doublet-Lattice Method with an unsteady source method for bodies to obtain a general method for oscillating wing/store configurations. Further applications of this new procedure to oscillating wing/body combinations have been made by Roos, et al[40]. The method of Morino et al.[8,9] can also be applied to wing-body combinations at both subsonic and supersonic speeds.

A standard configuration for wing-body interference calculations should include a fuselage and an optional store (nacelle)/pylon combination.

CONTROL SURFACES

The accuracy with which potential theory has been observed to predict the loading on interfering lifting surfaces or wing-body combinations decreases toward the trailing edge and the combined effects of thickness and viscosity (see Tijdeman's remarks above under Transonic Flow) probably explain discrepancies with experiment in hinge moment predictions. Accurate hinge moments are necessary to determine power requirements in active control systems for load alleviation and flutter suppression, as well as to predict flutter involving control surface motion. Some of the references cited in the preceding section account for thickness of wings as well as bodies. The additional effects of viscosity via a shear layer have been considered by Dowell, Ventres, and Yates[41,42,43]. The shear layer is an inviscid approximation to a viscous boundary layer.

ROTARY LOADS ON T-TAILS

The rotary loads are as important in predicting T-tail flutter characteristics as the rotary stability derivatives are in predicting lateral-directional stability and control characteristics of aircraft. Some of these require the ability to predict the spanwise distribution of induced drag of oscillating surfaces. Others require the rolling moments caused by oscillatory yaw and sideslip. The yawing moment induced by steady roll was discussed briefly by Kálmán et al.[44] and Hancock[45]. An accurate method for predicting spanwise distribution of induced drag in steady subsonic flow has been developed by Lan[46], and has been extended to the case of oscillatory motion in two-[47] and three-dimensions[48]. The oscillatory three-dimensional case permits the analysis of ornithopter propulsion[49] (as well as that of fish and birds!) as well as the oscillatory rotary loads on a T-tail. The oscillatory propulsion of interfering lifting surfaces in two-dimensional flow has also been considered by Bosch[50].

The problem of spanwise loading and rolling moments caused by oscillatory yawing and sideslipping has been studied by Isogai and Ichikawa[51], but only for incompressible flow.

The rotary aspects of T-tails have not been studied at Mach numbers above subsonic.

The standard AGARD T-tail configuration can provide a basis for comparison of calculated rotary loads.

INTERFERENCE EFFECTS OF VORTEX SHEDDING

Recent interest has been shown regarding the effects on steady loads and flutter of the leading-edge vortex separation from a highly-swept leading edge of either the delta or the swing-wing configuration. This is a nonlinear problem in the flow field geometry. Recent progress in predicting steady loads at subsonic speeds by panel and lattice methods has been made by Brune, et al.[52] and by Kandil, et al.[53] and a very complete bibliography is contained in Ref. 53. The unsteady subsonic case is currently under investigation.

The interference between wing-tip vortices and/or wing jet-flap wakes and horizontal tail load distributions has also attracted recent attention. The steady flow problem at subsonic speeds has been investigated by Goldhammer et al.[54] and by Shollenberger[55]. Extensions to unsteady flow are also under investigation[56,57]. Becker's investigation[57] of slender wing-tail configurations gave good correlation between prediction and measurement, but the predicted airforces were usually high.

The existing standard AGARD configurations are adequate for comparison of calculated nonlinear wake interference effects, although a horizontal tail with a smaller span than the wing might be a more practical configuration.

ROTATING BLADES

Significant progress has been made in adapting lifting surface theories to predict the loading of helicopter rotors. References 27, 28, 58-63 present various approaches and applications that all show promise as a replacement for Strip Theory. Numerical comparisons would appear to be timely in view of the importance of the helicopter in V-STOL Technology.

The Proceedings of a Workshop on Aeroelasticity in Turbomachines[64] indicates that the cascade problem is only being analyzed by two-dimensional methods. Recent developments in subsonic cascade theory for staggered compressor rotor blades have been made by Rao and Jones[65] and by Jones and Moore[66]. New solutions for supersonic cascades have been obtained by Verdon and McCune[67] and by Yates[68].

CONCLUDING REMARKS

A brief survey has been presented that illustrates a number of new aspects and refinements that have been made recently in unsteady aerodynamics for interfering configurations. Each topic is not only an interesting problem in its own right, but also is an important part of the whole problem of aerodynamic configurations, and the analysis of each has achieved a reasonable level of sophistication. This level of sophistication suggests that a program of comparing calculated results is feasible and could be a profitible experience for the contributors and beneficial to members of AGARD, in the same way that Refs. 1 and 2 have been useful.

Configurations and parameters would have to be agreed upon. A further study of supersonic interference among lifting surfaces requires no new configurations. Transonic flow studies would require a definition of thickness distributions; the NLR 7301 airfoil would be a good choice. The viscous aspects of transonic flow would require Reynolds numbers to be specified. Wing-body interference studies require a fuselage to be defined; at least one additional external-store/pylon configuration should also be considered. Control surface studies would require the planform description in addition to the airfoil thickness and Reynolds numbers; a definition of gaps and seals might also be considered. Rotary effects on T-tails can be calculated for the existing standard AGARD configuration, and calculations of vortex shedding characteristics can also be made on the existing standard configurations. Finally, studies of rotor blade loading would require a standard AGARD rotor blade along with its tip Mach number, advance ratio, and related parameters.

It is hoped that some of the above topics can become the basis of a third AGARD comparative study of computed results. The reference list presented here is only meant to be representative of the state-of-the-art; the author apologizes to the Panel for its American flavor.

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Table 1

Review of Calculation Methods for Unsteady Transonic Flow

	Author	Year	Ref.	Remarks
Two-dimensional methods	Stahara and Spreiter	1973	15	M $\approx$ 1.0
	Isogai	1974	16,17	no shock
	Dowell	1975	18	waves
	Revell	1973	19	layered-medium
	Ehlers	1973	20	finite difference
	Beam and Warming	1974	21	finite difference
	Ballhaus and Lomax	1974	22	finite difference
	Chan and Brashears	1974	23	finite element
	Traci, Farr, Albano & Cheng	1974	24	finite difference
	Magnus and Yoshihara	1975	25,26	finite difference
	Isom and Caradonna	1975	27,28	finite difference
Three-dimensional methods	Ruo and Theisen	1973	29	M $\approx$ 1.0
	Isogai	1974	17	no shock waves
	Cunningham	1973	30-32	mixed subsonic-supersonic method
	Garner	1975	33	semi-empirical
	Isom and Caradonna	1975	27,28	finite difference
	Weatherhill, Ehlers and Sebastian	1975	34	finite difference

REFERENCES

1. Woodcock, D. L. — A Comparison of Methods Used In Lifting Surface Theory. 1971, AGARD Rpt. No. 583, Supplement to the AGARD Manual on Aeroelasticity, Vol. VI.

2. Rodden, W. P. — A Comparison of Methods Used in Interfering Lifting Surface Theory. 1976, AGARD Rpt. No. 643, Supplement to the AGARD Manual on Aeroelasticity, Vol. VI.

3. Laschka, B. — Unsteady Aerodynamic Prediction Methods Applied in Aeroelasticity. AGARD Rpt. No. 645 on Unsteady Aerodynamics, May 1975.

4. McCroskey, W. J. — Some Current Research in Unsteady Aerodynamics - A Report from the Fluid Dynamics Panel. Paper presented at 46th Meeting of AGARD Propulsion and Energetics Panel, Monterey, Calif., 22-26 Sept. 1975.

5. Appa, K., and Jones, W. P. — Integrated Potential Formulation of Unsteady Aerodynamics for Interacting Wings. AIAA Paper No. 75-762, May 1975.

6. Cunningham, A. M., Jr. — Oscillatory Supersonic Kernel Function Method for Interfering Surfaces. J. Aircr., Nov. 1974, pp. 664-670.

7. Giesing, J. P., and Kálmán, T. P. — Oscillatory Supersonic Lifting Surface Theory Using a Finite Element Doublet Representation. AIAA Paper No. 75-76, May 1975.

8. Morino, L. — A General Theory of Unsteady Compressible Potential Aerodynamics. 1974, NASA CR-2464.

9. Morino, L., Chen, L. T., and Suciu, E. O. — Steady and Oscillatory Subsonic and Supersonic Aerodynamics Around Complex Configurations. AIAA J., March 1975, pp. 368-374.

10. Brock, B. J., and Griffin, J. A., Jr. — The Supersonic Doublet-Lattice Method - A Comparison of Two Approaches. AIAA Paper No. 75-760, May 1975.

11. Roger, K. L. — Applications of the Unsteady Uniform Pressure Lifting Surface Element. Paper presented to Aerospace Flutter and Dynamics Council, Orlando, Florida, 29 April 1976.

12. Chipman, R. R. — An Improved Mach-Box Approach for the Calculation of Supersonic Oscillatory Pressure Distributions. Proceedings, AIAA/ASME/SAE 17th Structures, Structural Dynamics, and Materials Conf., 5-7 May 1976, pp. 615-625.

13. Schmid, H. — A Supersonic Lifting Surface Theory for Predicting Unsteady Interference Airloads on Coplanar Wing-Horizontal-Tail Configurations. MBB Report AN-P-0001, 1975.

14. Tijdeman, H. — On the Unsteady Aerodynamic Characteristics of Oscillating Airfoils in Two-Dimensional Transonic Flow. Paper presented at ONR Transonic Flow Conf., Univ. of California, Los Angeles, 30-31 March 1976.

15. Stahara, S., and Spreiter, J. R. — Development of a Nonlinear Unsteady Transonic Flow Theory. 1973, NASA CR-2258.

16. Isogai, K. — Unsteady Transonic Flow over Oscillating Circular Arc Airfoils. AIAA Paper 74-360, April 1974.

17. Isogai, K. — A Method for Predicting Unsteady Aerodynamic Forces on Oscillating Wings with Thickness in Transonic Flow near Mach Number 1; Part I: Two-dimensional Theory; Part II: Rectangular Wings. June 1974, NAL Report TR-368 T.

18. Dowell, E. H. — A Simplified Theory of Oscillating Airfoils in Transonic Flow. Paper presented at the Symposium on Unsteady Aerodynamics, Univ. of Arizona, Tucson, March 1975.

19. Revell. J. D. — Research on Unsteady Transonic Flow Theory. 1973, NASA CR-112114.

20. Ehlers, F. E. — A Finite Difference Method for the Solution of the Transonic Flow Around Harmonically Oscillating Wings. 1973, NASA CR-2257. See also AIAA Paper 74-543, June 1974.

21. Beam, R. M., and Warming, R. F. — Numerical Calculations of Two-dimensional Unsteady Transonic Flow with Circulation. Feb. 1974, NASA TN-D 7605.

22. Ballhaus, W.F., and Lomax, H. — The Numerical Simulation of Low Frequency Unsteady Transonic Flow Fields. Proc. of the 4th International Conf. on Numerical Methods in Fluid Dynamics. Univ. of Colorado, Boulder, June 1974.

23. Chan, S. T. K., and Brashears, M. R. — Finite Element Analysis of Transonic Flow. Tech. Report AFFDL-TR-74-11, 1974. See Also AIAA Paper 75-875, June 1975.

24. Traci, R. M., Albano, E. D., Farr, J. L., and Cheng, H. K. — Small Disturbance Transonic Flows About Oscillating Airfoils. Tech. Report AFFDL-TR-74-37, 1974. See Also AIAA Paper 75-877, June 1975.

25. Magnus, R. J., and Yoshihara, H. — Calculations of Transonic Flow over an Oscillating Airfoil. AIAA Paper 75-98, Jan. 1975.

26. Ballhaus, W. F., Magnus, R. J., and Yoshihara, H. — Some Examples of Unsteady Transonic Flow over Airfoils. Paper Presented at the Symposium on Unsteady Aerodynamics, Univ. of Arizona, Tucson, 18-20 March 1975.

27. Isom, M. P. — Unsteady Subsonic and Transonic Potential Flow over Helicopter Blades. October 1974, NASA CR-2463.

28. Caradonna, F. S., and Isom, M. P. — Numerical Calculation of Unsteady Transonic Potential Flow over Helicopter Rotor Blades. AIAA Paper 75-168, Jan. 1975.

29. Ruo, S. Y., and Theisen, J. G. — Calculation of Unsteady Transonic Aerodynamic for Oscillating Wings with Thickness. 1973, NASA CR-2259. See also AIAA Paper 73-316, March 1973.

30. Cunningham, A. M., Jr. — The Application of General Dynamic Lifting Surface Elements to Problems in Unsteady Transonic Flow. 1973, NASA CR-112264.

31. Cunningham, A. M., Jr. — An Oscillatory Kernel Function Method for Lifting Surfaces in Mixed Transonic Flow. AIAA Paper 74-359, April 1974.

32. Cunningham, A. M., Jr. — Further Developments in the Prediction of Oscillatory Aerodynamics in Mixed Transonic Flow. AIAA Paper 75-99, Jan. 1975.

33. Garner, H. C. — A Practical Approach to the Prediction of Oscillatory Pressure Distributions on Wings in Supercritical Flow. Feb. 1975, RAE TR 74181.

34. Weatherill, W. H., Ehlers, F. E., and Sebastian, J. D. — Computation of the Transonic Perturbation Flow Fields Around Two- and Three-dimensional Oscillating Wings. Dec. 1975, NASA CR-2599.

35. Gray, R., and Davies, D. E. — Comparison of Experimentally and Theoretically Determined Values of Oscillatory Aerodynamic Control Surface Hinge Moment Coefficients. RAE Technical Report 72023, March 1972.

36. Ashley, H. and Rodden, W. P. — Wing-Body Aerodynamic Interaction. Annual Review of Fluid Mechanics, Vol. 4, 1972, pp. 431-472.

37. Giesing, J. P., Kálmán, T. P., and Rodden, W. P. — Subsonic Steady and Oscillatory Aerodynamics for Multiple Interfering Wings and Bodies. J. Aircr., Oct. 1972, pp. 693-702.

38. Labrujere, T. E., and Sytsma, H. A. — Aerodynamic Interference Between Aircraft Components: the Possibility of Prediction. Aug. 1972, ICAS Paper No. 72-49.

39. Bennekers, B., Roos, R., and Zwaan, R. J. — Calculation of Aerodynamic Loads on Oscillating Wing/Store Combinations in Subsonic Flow. Oct. 1974, NLR Rpt. MP 74028U.

40. Roos, R., Bennekers, B., and Zwaan, R. J. — A Calculation Method for Unsteady Subsonic Flow about Harmonically Oscillating Wing-Body Combinations. AIAA Paper No. 75-864, 1975.

41. Dowell, E. H., and Ventres, C. S. — Derivation of Aerodynamic Kernel Functions. AIAA J., Nov. 1973, pp. 1586-1588.

42. Yates, J. E. — Linearized Integral Theory of Three-Dimensional Unsteady Flow in a Shear Layer. AIAA J., May 1974, pp. 596-602.

43. Ventres, C. S. — Shear Flow Aerodynamics: Lifting Surface Theory. AIAA J., Sept. 1975, pp. 1183-1189.

44. Kálmán, T. P., Giesing, J. P., and Rodden, W. P. — Spanwise Distribution of Induced Drag in Subsonic Flow by the Vortex Lattice Method. J. Aircr., Nov.-Dec. 1970, pp. 574-576.

45. Hancock, G. J. — Comment on "Spanwise Distribution of Induced Drag in Subsonic Flow by the Vortex Lattice Method." J. Aircr. Aug. 1971, p. 681. Also, Reply by Authors to G. J. Hancock, J. Aircr., Aug. 1971, pp. 681-682.

46. Lan, C. E. — A Quasi-Vortex-Lattice Method in Thin Wing Theory. J. Aircr., Sept. 1974, pp. 518-527.

47. Lan, C. E. — The Induced Drag of Oscillating Airfoils in Linear Subsonic Compressible Flow. June 1975, Rpt. KU-FRL-400, Univ. of Kansas.

48. Lan, C. E. — Some Applications of the Quasi Vortex-Lattice Method in Steady and Unsteady Aerodynamics. Paper presented at Vortex-Lattice Workshop, NASA Langley Research Center, 17-18 May 1976.

49. Bennett, A. G., Obye, R. C., and Jeglum, P. M. — Ornithopter Aerodynamic Experiments. Swimming and Flying in Nature, Vol. 2, Plennum Press, 1975, pp. 985-1000, ed. by T.Y.-T. Wu, C. J. Brokaw, and C. Brennen.

50. Bosch, H. — Instationäre Luftkräfte eines Tragflügelpaares Strömung. Diplom-Ingenieur Thesis, Technical University, Munich, 1972.

51. Isogai, K., and Ichikawa, T. — Lifting-Surface Theory for a Wing Oscillating in Yaw and Sideslip with an Angle of Attack. AIAA J., May 1973, pp. 599-606.

52. Brune, G. W., Weber, J. A., Johnson, F. T., Lu, P., and Rubbert, P. E. — A Three-Dimensional Solution of Flows over Wings with Leading-Edge Separation; Part 1: Engineering Document. Sept. 1975, NASA CR-132709.

53. Kandil, O. A., Mook, D. T., and Nayfeh, A. H. — Nonlinear Prediction of Aerodynamic Loads on Lifting Surfaces. J. Aircr., Jan. 1976, pp. 22-28.

54. Goldhammer, M. I., Lopez, M. L., and Shen, C. C. — Methods of Predicting the Aerodynamic and Stability and Control Characteristics of STOL Aircraft; Vol. 1: Basic Theoretical Methods. Dec. 1973, AFFDL-TR-73-146-Vol. 1.

55. Shollenberger, C. A. — A Three-Dimensional Wing/Jet Interaction Analysis Including Jet Distortion Influences. J. Aircr., Sept. 1975, pp. 706-713.

56. Suciu, E. O., and Morino, L. — A Nonlinear Finite-Element Analysis of Wings in Steady Incompressible Flows with Wake Roll-up. AIAA Paper No. 76-64, Jan. 1976.

57. Becker, J. — Vergleich gemessener und berechneter instationärer Druckverteilungen für den hohen Unterschall an einem elastichen gepfeilten Flügel, MBB Company Report EWR-Nr. 403-69, Sept. 1969.

58. Ichikawa, T. — Linear Aerodynamic Theory of Rotor Blades. J. Aircr., May-June 1967, pp. 210-218.

59. Dat, R. — Représentation D'une Ligne Portante Animée D'un Mouvement Arbitraire, Par Une Ligne de Doublets D'Acceleration. Rech. Aérosp., No. 133, Nov.-Dec. 1969, pp. 45-51.

60. Costes. J. J. — Calcul Des Forces Aérodynamiques Instationnaires Sur Les Pales D'un Rotor D'Hélicoptère. Rech. Aérosp., No. 2, Mar.-Apr. 1972, pp. 91-106.

61. Runyan, H. L. — Unsteady Lifting Surface Theory Applied to a Propeller and Helicopter Rotor. Ph.D. Thesis, Loughborough Univ. of Tech., July 1973.

62. Dat, R. — La Théorie de la Surface Portante Appliquée a L'Aile Fixe et a L'Helice. Rech. Aérosp., No. 4, Jul.-Aug. 1973, pp. 245-254.

63. Hammond, C. E., Runyan, H. L., and Mason, J. P. — Application of Unsteady Lifting Surface Theory to Propellers in Forward Flight. AIAA Paper No. 74-419, April 1974.

64. Fleeter, S., ed. — Aeroelasticity in Turbomachinery. Proceedings of a Workshop held at Detroit Diesel Allison, 1-2 June 1972, sponsored by ONR Project Squid.

65. Rao, B. M., and Jones, W. P. — Unsteady Airloads on a Cascade of Staggered Blades in Subsonic Flow. Paper No. 177, Proceedings of AGARD Symposium on Unsteady Phenomena in Turbomachinery, Naval Postgraduate School, Monterey, Calif., Sept. 1975.

66. Jones, W. P., and Moore, J. A. — Aerodynamic Theory for a Cascade of Oscillating Airfoils in Subsonic Flow. AIAA J., May 1976, pp. 601-605.

67. Verdon, J. M., and McCune, J. E. — Unsteady Supersonic Cascade in Subsonic Axial Flow. AIAA J., Feb. 1975, pp. 193-201.

68. Yates, J. E. — Analysis of Supersonic Unsteady Cascades with the Method of Characteristics, Vol. I; Users Manual, Supersonic Unsteady Cascade Program, Vol. II. AFFDL-TR-75-159, Dec. 1975.

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Unsteady flow	Mathematical prediction

14. Abstract

The accurate prediction of unsteady air loads is essential to avoiding problems and assuring safety in the many interdisciplinary regions involving aeroelasticity and the dynamics of active controls. However, the methods to predict such airloads are complex and intricate. It was considered essential to specify standard configurations and parameters, and to encourage pioneering NATO scientists to report their results early. This would provide bases for evaluation and improvement of later and following developments by other countries. The first co-operative effort involved isolated surfaces in subsonic and supersonic flow, and is reported by D.L.Woodcock in AGARD Report No.583 ("A Comparison of Methods Used in Lifting Surface Theory", 1971). The noticeable success led to another effort on interfering lifting surfaces and is reported by W.P.Rodden in AGARD Report No.643 ("A Comparison of Methods Used in Interfering Lifting Surface Theory", 1976). Both are supplements to the AGARD Manual on Aeroelasticity, Vol.VI. The latter effort and report has also proved to be highly successful.

New developments are rapidly emerging in unsteady aerodynamics. The aeroelastician will continue heavy reliance on prediction of airloads from theoretical methods. A terse description of the new state of the art ~~was required and has been very competently~~ is provided ~~by Dr Rodden~~ in this report.

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